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Optical Properties of Marine Stratocumulus Clouds Modified by Ship Track Effluents

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1. Introduction

The angular distribution of scattered radiation deep within a cloud layer was measured in marine stratocumulus clouds modified by the emissions from ships. These observations, obtained at thirteen discrete wavelengths between 0.5 and 2.3 μm, were obtained as the University of Washington Convair C-131A aircraft flew through a pair of roughly parallel ship tracks off the coast of southern California on 10 July 1987.

In the first of these ship tracks, the cloud droplet concentration increased from 40 cm^{-3} to 107 cm^{-3} (125 cm^{-3} in the second ship track). Simultaneous to this spectacular change, the aircraft measured interstitial aerosol (Aitken nucleus) concentration that increased from 400 cm^{-3} to 1000 cm^{-3} and cloud liquid water content that increased from 0.30 g m^{-3} to 0.75 g m^{-3}. Broadband pyranometer measurements showed that the upwelling flux density increased from 150 W m^{-2} to 280 W m^{-2}. These *in situ* microphysics and broadband pyranometer results, together with AVHRR satellite images obtained with the NOAA-10 satellite, are described in detail by Radke et al. (1989).

In this paper, we present internal scattered radiation measurements at selected wavelengths obtained with the cloud absorption radiometer (King et al. 1986) for a 100 km section of marine stratocumulus clouds containing these two ship track features.

2. Results from observations on 10 July 1987

On 10 July 1987 the C-131A was flying within a marine stratocumulus cloud layer enroute to a planned mission with the ER-2 aircraft when it encountered two regions approximately 17 km in width that were apparently modified by the effluents from ships. The C-131A was primarily making cloud radiation and cloud microphysics measurements deep within the cloud layer, which was located ~300 km from the airfield on Coronado Island, San Diego.

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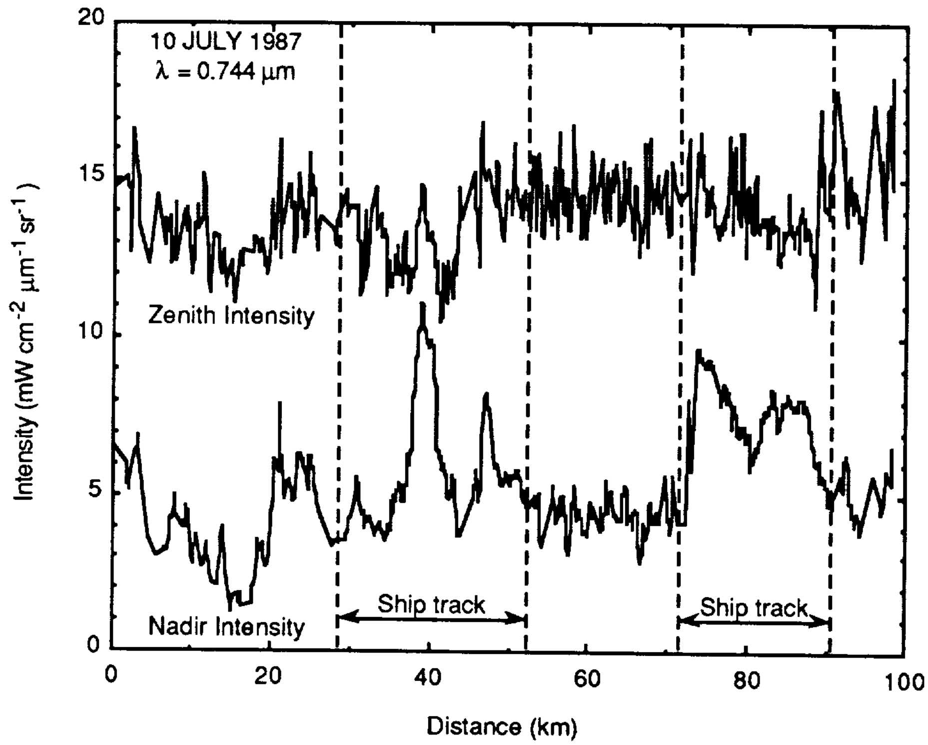

Fig. 1. Zenith and nadir intensities as a function of distance for measurements obtained inside the clouds between 8:49 and 9:10 PDT. These measurements were obtained at a wavelength $\lambda = 0.744$ μm.

Figures 1 and 2 illustrate the zenith and nadir intensities as a function of distance (time) for measurements obtained inside clouds for a 100 km section of this cloud. These data, corresponding to observations obtained with the cloud absorption radiometer at 0.744 and 2.20 μm, respectively, show that the zenith and nadir intensities were substantially modified by the effluents from the ships. At λ = 0.744 μm (Fig. 1), the upwelling (nadir) intensity increased from approximately 4 to 11 mW cm^{-2} μm^{-1} sr^{-1} in the first ship track, with a somewhat less dramatic, though more uniform, increase in the second ship track. The downwelling (zenith) intensity, on the other hand, showed a modest decrease in both ship tracks. These changes are consistent with the fact that the total optical thickness of the cloud layer increased, and are a direct consequence of the observation that the total concentration and concentration of small droplets increased, while the mean droplet radius decreased. In fact, Radke et al. (1989) estimate, based on these microphysical changes, that the total optical thickness of the cloud layer increased by a factor of ~2.6 in the first ship track (2.1 in the second ship track).

At λ = 2.20 μm (Fig. 2), both the upwelling (nadir) and downwelling (zenith) intensities decreased within the ship tracks. Again, the change is the most dramatic and the least uniform in the first ship track. The explanation for these changes can be understood as follows. As the optical thickness in-

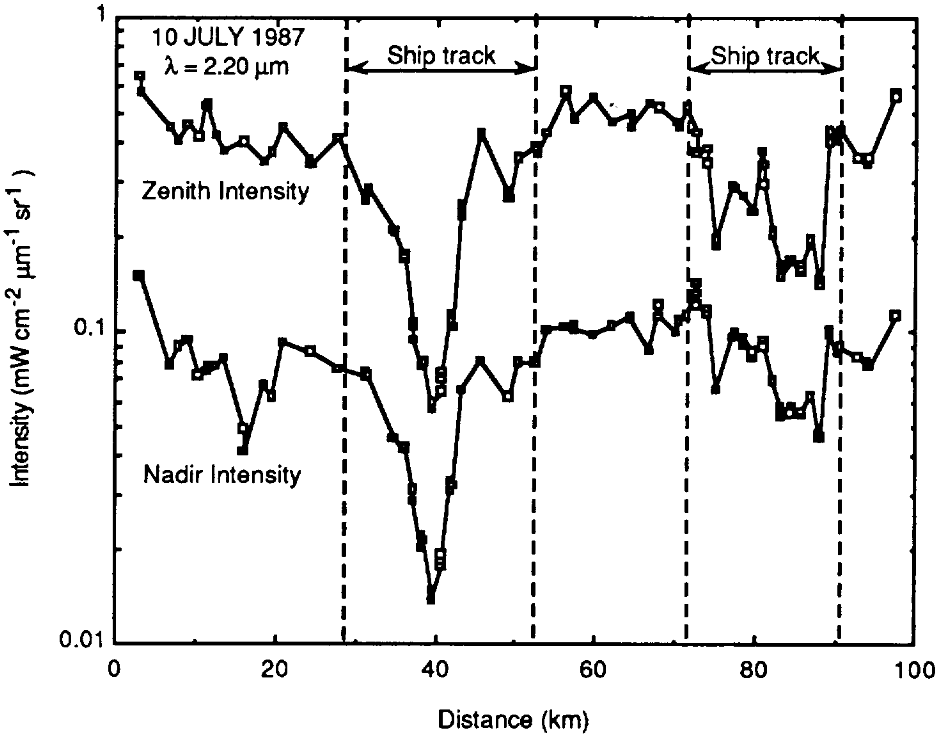

Fig. 2. As in Fig. 1 except for $\lambda = 2.20\ \mu m$.

creases, the additional scattering leads to increased attenuation of solar radiation at this absorbing wavelength. The intensity distribution is thus reduced in all directions within the cloud. This is not the case for reflected solar radiation, on the other hand, since increasing the optical thickness will always lead to increasing the reflection function at all wavelengths.

Figures 1 and 2 represent dramatically different similarity parameters, and hence single scattering albedos, within the cloud (cf. King et al. 1989). At λ = 0.744 μm the single scattering albedo $\omega_0 \sim 1.0$, whereas at λ = 2.20 μm $\omega_0 \sim 0.99$. In order to examine the transition of the zenith and nadir intensities as the single scattering albedo, and hence wavelength, varies, we have examined the nadir intensity (Fig. 3) and zenith intensity (Fig. 4) as a function of distance for selected wavelengths between 0.744 and 2.20 μm. The curves for 0.744 and 2.20 μm are the same as those presented in Figs. 1 and 2. For the zenith intensity (Fig. 3), the transition from an enhanced intensity at 0.744 μm to a reduced intensity a 2.20 μm is striking. At some wavelength between 1.20 and 1.64 μm, these result suggest that the changes in the optical properties of the cloud resulting from ship track effluents would be imperceptible. The broadband pyranometer measurements, which integrate over all angles and the entire solar spectrum, follow very closely the changes at 0.744 μm (cf. Radke et al. 1989).

For the zenith (downwelling) intensity, illustrated in Fig. 4, the intensity decreases at all wavelengths, though the reduction at 0.744 μm is extremely

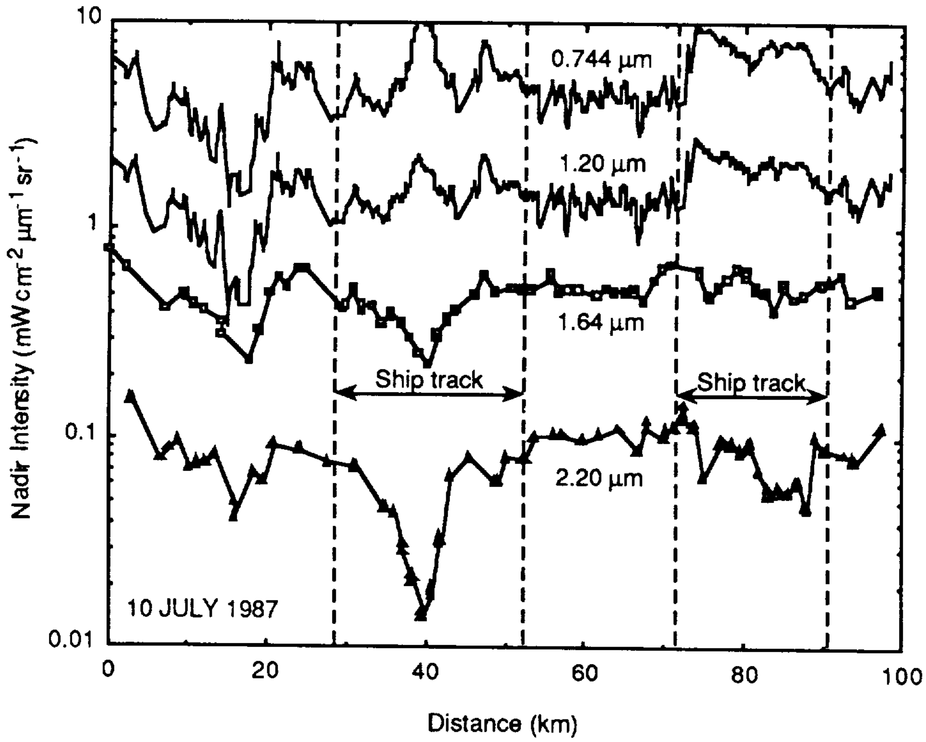

Fig. 3. Nadir (upwelling) intensities as a function of distance for measurements obtained inside the clouds between 8:49 and 9:10 PDT. These measurements were obtained at selected wavelengths between 0.744 and 2.20 μm.

small, as noted above (cf. Fig. 1). The effects of increasing absorption (wavelength) are quite apparent in this figure. The broadband pyranometer, which again reflects primarily the measurement at nonabsorbing wavelengths near 0.744 μm, showed that the zenith (downwelling) flux density is virtually unchanged in the ship tracks, as expected from an examination of Fig. 4.

Though the major changes in the internal scattered radiation field within the ship track events of these marine stratocumulus clouds can be explained by changes in cloud optical thickness, both above and below the aircraft, it is conceivable that soot particulates from the ship exhaust could also affect the spectral intensity field within the clouds. In fact, one would expect that, in addition to increasing optical thickness by the emission of cloud condensation nuclei, the ship exhaust might lead to increased absorption by the cloud droplets. Two competing effects are possible: 1) increasing absorption from aerosols, either as a result of dirty water or interstitial aerosol; or 2) decreasing absorption because the cloud droplets are smaller. Our initial analysis, based on the diffusion domain method of King et al. (1989), shows that the latter effect dominates. In the first ship track the effective radius computed from the in situ cloud droplet size distribution decreases from 12.5 to 10.5 μm, and in the second ship track from 11.2 to 7.5 μm (Radke et al. 1989).

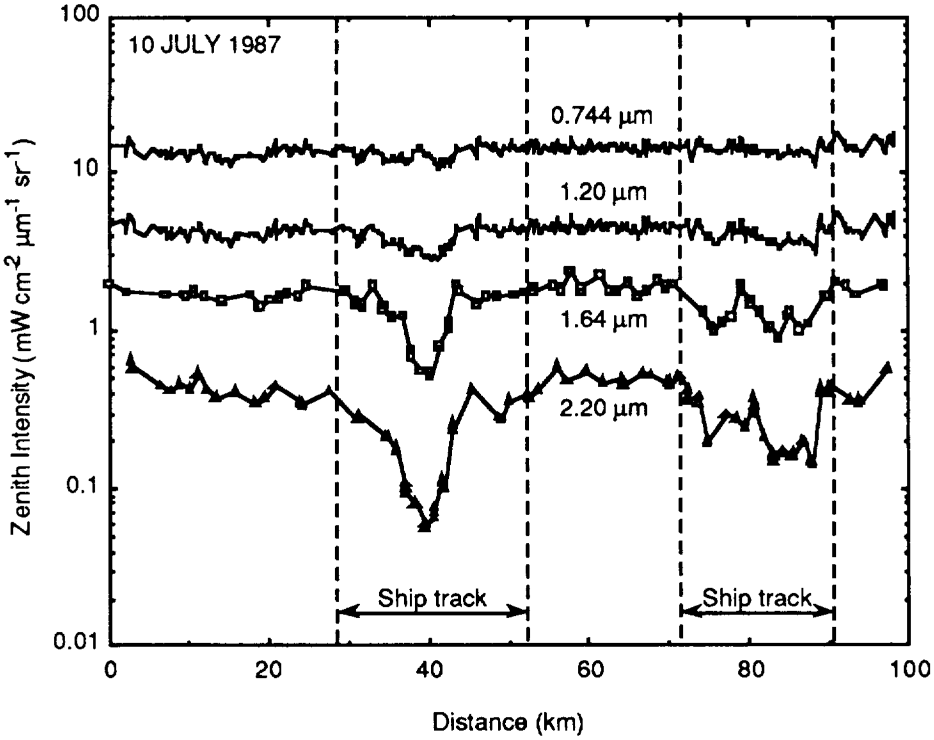

Fig. 4. As in Fig. 3 except for zenith (downwelling) intensities.

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